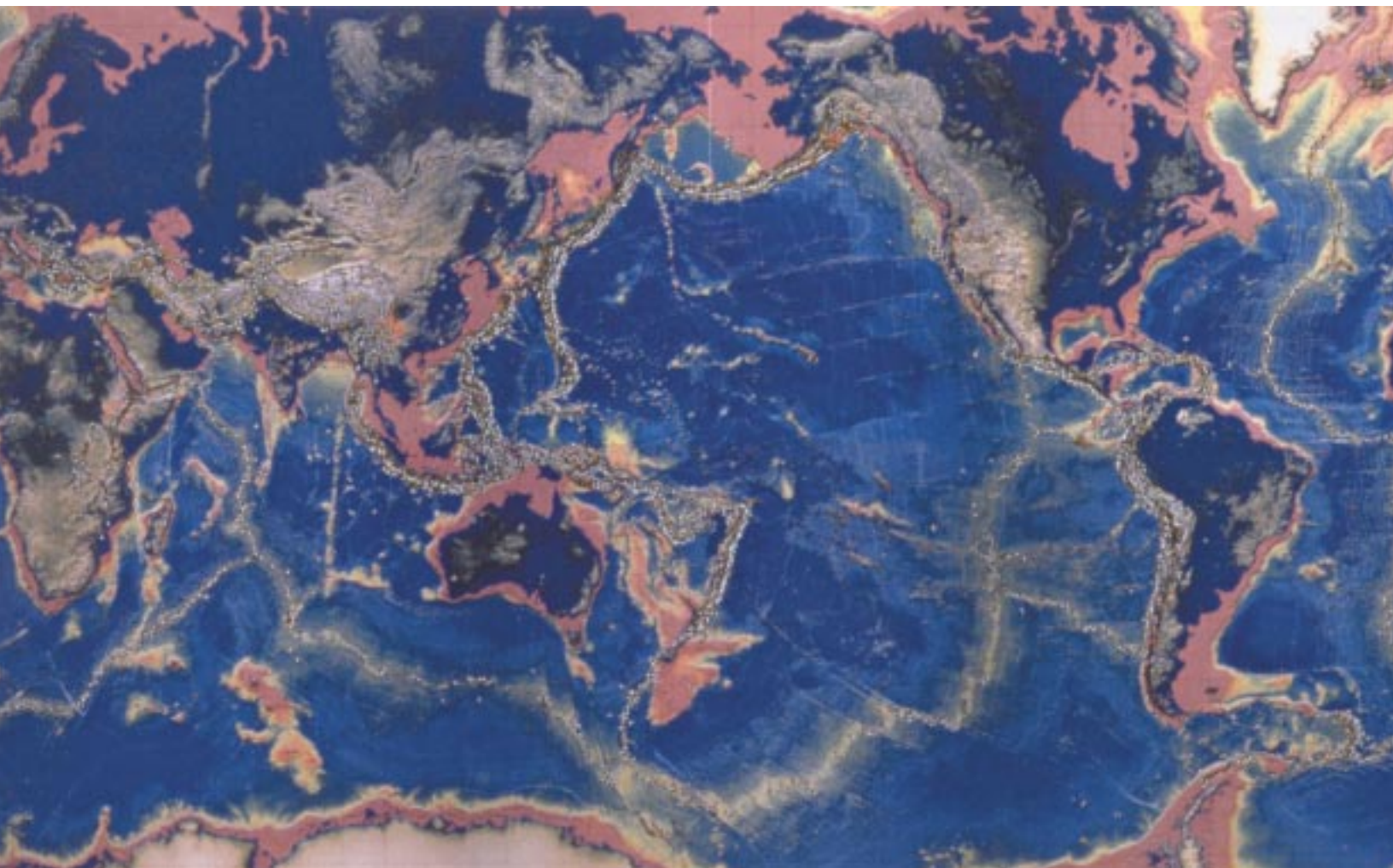




The theory of the mantle as a pot on a stove, being heated from below by the core, was by and large invented in England. . . . In this country, however, we like to put ice cubes in our drinks. . . . Perhaps that is why some of us believe that the mantle . . . is cooled from above by ancient continents and subducting



slabs poking down into the mantle like ice cubes.



The Inside of Earth: Deep-Earth Science from the Top Down

by Don L. Anderson



This global tectonic map shows plates, volcanoes, and earthquakes, as well as the age of the ocean floor (white lines). This map can be used to infer the tectonic context of volcanoes and volcanic chains. (Prepared in cooperation with David Sandwell, UC San Diego.)

Earth is really several planets. Which planet you see depends on where you view it from. Looking at it from outside, from space, stripped of clouds, you can see that Earth has two quite different hemispheres—a continent hemisphere and an ocean hemisphere. The latter, the Pacific hemisphere, is underlain almost entirely by one gigantic tectonic plate—a continuous chunk of Earth's crust—which is diving under what is called the ring of fire because of the volcanoes that line the plate boundary along Oregon, Washington State, British Columbia, the Aleutians, the Kuriles, Japan, the Marianas, Tonga-Fiji, South America, and Central America. There are also volcanoes in other places: along other plate boundaries on the sea-floor and in island chains throughout the Pacific. One of the unanswered questions in geology is: why are there volcanoes in some places? In my own work, I turn the question around and ask: why aren't there volcanoes everywhere? For seismology tells us that there is a semimolten layer underneath the plate almost everywhere. Something is keeping it down.

The answer has to do with Earth's outer shell, the lithosphere, which is under lateral compression almost everywhere; it's as if it were tied down, keeping a lid on the lava below. Earth has a lot of melt under that outer shell. If the lithosphere were not under compression, lava would be leaking out everywhere, and we would all be in danger of getting covered by lava flows. Arches and the decks of suspension bridges work the same way: take away the lateral compression and they fall apart.

Continents are part of the lithosphere. The continents break up and reassemble every 400 or 500 million years or so. About 750 million years ago, Earth's continental fragments were assembled as a supercontinent in one hemisphere. Another supercontinent formed about 250 million years ago and broke up about 100 million years later. (And I predict we'll have another one 250 million years from now.) During these supercontinent time periods, the opposite hemisphere would have been completely covered by ocean. Now, continents have a very important effect on the underlying mantle; they serve to insulate it. What the planet looks like inside depends on whether a supercontinent is insulating the hemisphere or whether the heat has been allowed to escape through an ocean basin. Seismologists have been trying to see inside Earth to understand how the properties of the planet vary with depth, all the way down to the inner core. We are now trying to determine whether the hemispheres maintain their differences far below the surface, and we are finding that the changes from place to place are as important

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The Little Prince cleans
out his volcanoes (above)
and Dante stratifies the
sinners (right).

as the changes from one depth to another.

People have wondered about the inside of Earth for a long time. Dante was the first, in his *Inferno*, to draw internal shells with names. As in the 700-year-old drawing below, he imagined the lightweight sinners—the lustful, the heretics—residing in the outer shells, and the heavyweight sinners—traitors to country, to guests, and to masters—down toward the bottom of what would be the mantle. Satan, the biggest sinner of all, lived in the inner core at the center of Earth.

About 350 years ago René Descartes also proposed a layered Earth, which is very similar to the present views of some Earth scientists. He thought the inside of Earth was primordial matter—stardust, bits of heaven. This primordial-matter idea is pretty much up-to-date. As it turns out, we now believe the mantle is made up of the same stuff as the meteorites, which are leftovers from the primitive solar system. The question is: does any of this primordial material survive today, deep inside Earth, or was it all melted and separated as Earth grew?

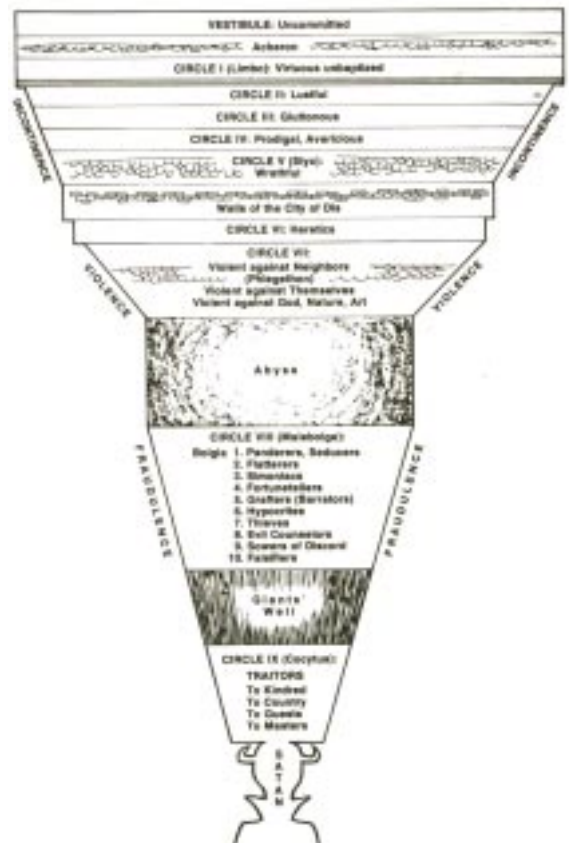
Later in the 17th century, a German Jesuit named Kirschner came up with a fairly sophisticated idea of what was happening inside the planet. He imagined giant tubes of molten rock, lava, and hot air blowing up toward the surface, intersecting tubes of cool, outside air near the outer part of Earth, creating huge volcanoes. Basically, wind was driving the interior fires. He had the idea that if you kept all your volcanoes cleaned out, they wouldn't erupt, so he invented a machine to clean out volcanoes. If this sounds familiar, you may be remembering *The Little Prince*, by Antoine de Saint-Exupéry (1943). The Little Prince was from a little planet with three volcanoes. Every time he left the planet, just to be safe, he would clean out his volcanoes and bank their fires.

These ideas may sound fanciful, but they are remarkably current. In 1971 Jason Morgan and in 1995 Roger Larson (and many agree with them)

postulated that the core-mantle boundary—what Dante would call the boundary between hell and nether hell—coughs up giant hot plumes that are responsible for volcanoes at Earth's surface. Morgan's are little plumes, the radius of a volcano, and Larson has megaplumes, the size of North America. So, there's a great similarity between older and newer views of Earth; the very old one isn't based on much data, and I'll get back to the modern one later.

Other ideas about Earth have been fashionable at various times. Studies of the Atlantic hemisphere led to the concept of an expanding Earth: new crust was clearly being formed, but there was no obvious place that the crust was going. Others have assumed from looking at mountain belts that the planet was contracting. If you fly over the Alps, you might conclude that Earth was shriveling up like a dried apple.

Actually, Earth is a very hot planet and always has been. Giant impacts were very important in setting the planet's thermal state, as recent research has made clear. We now think that the moon was generated by another planet hitting Earth when Earth was somewhat smaller. The impact splashed out so much molten magma that remnants of it condensed in orbit and formed the moon. The impact also melted Earth—even if it had already been cooling off and crystallizing, it would have been reset to a molten stage. And



there have been several of these large impacts strewn through Earth's history. The Cretaceous/Tertiary extinction event eliminated a large portion of life on the planet. The impact that created the moon would not only have extinguished all life, if there had been any, but also would have literally liquidated all the rocks and the geology. Earth would have had to start from a hot state again. And our hot planet is livable only because a strong shell holds the hot interior down.

Any way you look at it, Earth started very hot and has been cooling down ever since. Somewhere between a quarter and a half of all the heat currently coming out of Earth is original heat. Although Earth has cooled off quite a bit, the upper mantle, just beneath the outer shell, is held at the melting temperature. It will take much more time before the mantle is completely frozen.

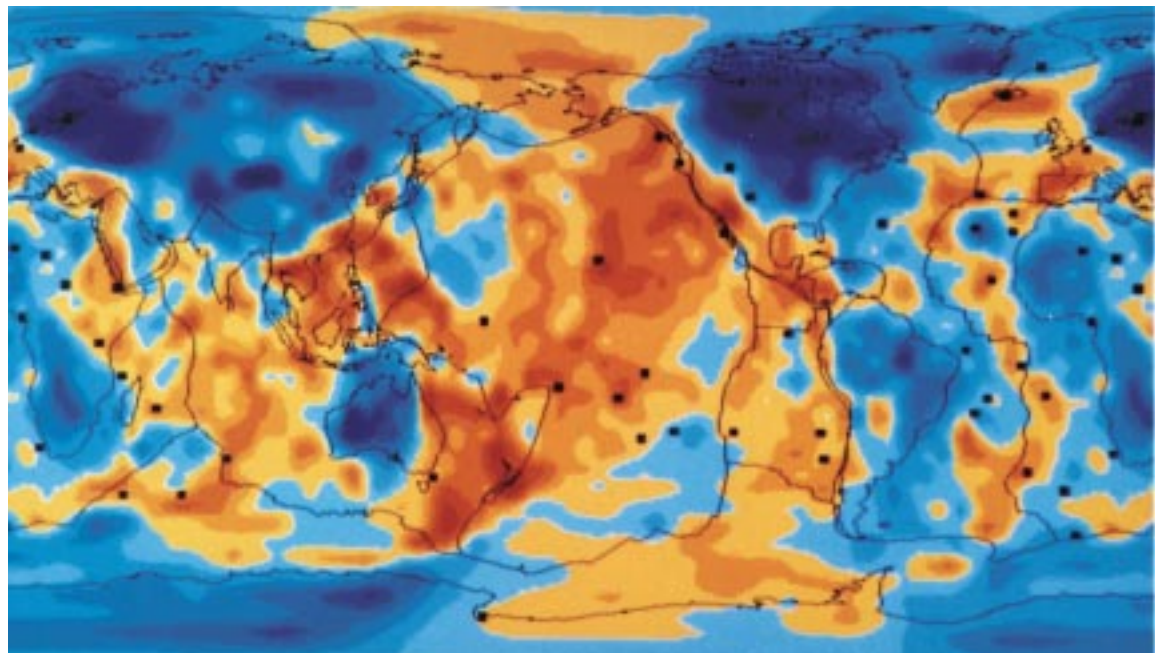
How do we know that it's hot down there? A science known as seismic tomography has enabled us to see inside Earth so that we have a better view than Dante or Descartes. Tomography is similar to medical imaging—we can CAT scan Earth. To get these images, seismologists make use of earthquakes, which send out “rays” that illuminate the interior. We actually measure seismic velocities—the time it takes for a wave generated by an earthquake to travel from the earthquake to a seismic station or a seismometer. It's like a flash of lightning. When lightning flashes, for a brief moment you can see all kinds of things around you, but then the light vanishes and you have to wait for another one to be able to see again. And if you move to another place, you'll see things during a lightning flash that you didn't see with the first bolt. After enough earthquakes and with enough seismic stations scattered over the surface, we can illuminate the planet's whole interior. Today we

have a good picture of the interior structure at almost every depth and under almost every place. By comparing these images with global maps of the surface, we can find out why continents drift and what causes volcanoes and earthquakes.

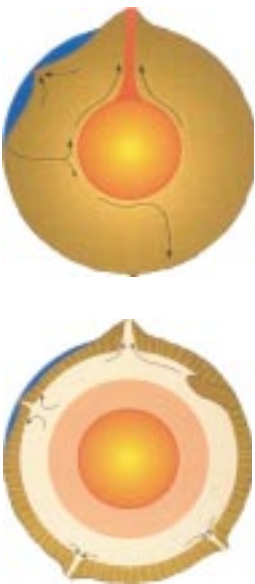
Now, we know that the mantle is made up of rock, although it's under such tremendous pressure and at such a high temperature that it flows, much like glaciers or warm asphalt. We also know that, all other things being equal, seismic waves from earthquakes travel faster in colder solids because they are denser. Seismology has shown us that the speed of a seismic wave doesn't increase with depth in the outer 100–200 kilometers of the mantle in most places below the crust, but actually decreases. That's not what you would expect of a solid that's being pressed under the weight of the lithosphere. But it *is* what you'd expect if the shallow mantle is partially molten. High temperatures and partial melting in the mantle slow the wave down. So this slowing of seismic waves in the outer 100–200 kilometers means that they are traveling through a magma-rich region underneath the high-velocity, strong, cold lid that holds it down. This “magma sphere” exists under oceanic and mountainous regions and around the ring of fire. It may not exist under the oldest parts of continents (the dark blue regions in the map below).

Other research on temperatures inside Earth also points to melting beneath the plates. Estimates of the interior temperature show that it's close to or above the melting point in the upper mantle just in the region where we've found this low-velocity zone. This has likely been the case throughout Earth's history—at least the past 2.5 billion years. Geology professors Ed Stolper and Peter Wyllie, with their colleagues at Caltech, have shown that

This early (1984) Caltech tomographic map shows Earth at a depth of 170 kilometers. The blue regions are centered on the oldest parts of the continents, indicating that they have deep, cold roots. The red regions are mainly in young oceans and tectonically active areas such as California. The Pacific mantle is seismically slow (hot). “Hotspots” (block dots) generally occur above broad, hot regions of the shallow mantle, often along fracture zones or old ridges. (I. Nakanishi, H.C. Nataf, and D. L. Anderson)



Shown below are two extreme views of the sources of so-called midplate, or hotspot, volcanoes. The upper globe shows the plume, or megaplume, hypothesis, in which volcanoes such as those in Hawaii and Iceland sit atop a hot plume that extends to Earth's core.



The lower globe illustrates the view that the upper mantle is hot enough almost everywhere to supply magma through cracks in the outer shell. Most of Earth's outer shell is under compression, but in some places it is being pulled apart, allowing the underlying magma to escape as a volcano.

rocks melt at much lower temperatures than was previously believed. So the sciences of seismology and petrology agree on the likelihood of melting in the upper mantle. Other recent work shows that temperatures in the shallow mantle are higher than commonly assumed.

It's hard to avoid the conclusion that there is magma in the upper mantle. This leads back to my original question: why don't we have volcanoes everywhere? Why does this hot mantle push through in only certain places? In order to answer this question, I'll be discussing two completely different ways of looking at Earth.

One point of view, the hotspot or plume hypothesis, speculates that plumes of hot mantle come up to the surface from the core-mantle boundary. This hypothesis proposes that the core is heating up the base of the mantle, causing large buoyant plumes to rise, and that every active volcano that's not at a plate boundary is connected to a hot, narrow upwelling that goes all the way down to the core-mantle boundary. This is often referred to as the pot-on-the-stove analogy.

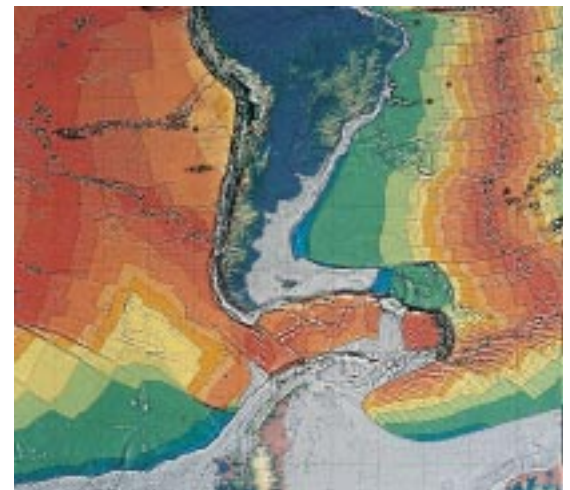
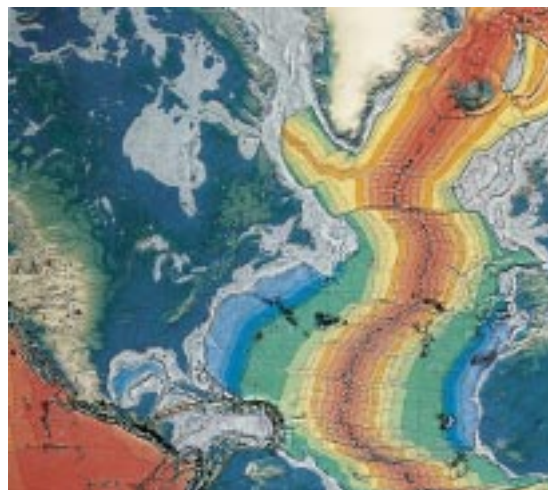
The alternative point of view is that magma, which can be very shallow, comes up through cracks in the lithosphere. In fact, magma can break rocks and make its own cracks, a process called "magma fracture." So Earth scientists have to try to determine which one of these models is true: do we need to import heat from the core-mantle boundary to the top to get molten rock, or do we already have molten rock at the top and just need to make a crack to let that magma out? The question then becomes: do plumes cause the cracks and volcanoes to form? Or do plate tectonics and lithospheric architecture control the locations of cracks and volcanoes?

First, I'd like to explain a little about how plate

tectonics works. Tectonic plates are those parts of Earth's outer shell that are under compression. Plates break when they're released from compression and get stretched out; we call this "going into extension." Compression holds plates together; extension allows them to break. For example, the mid-Atlantic ridge is a very large crack in the middle of the Atlantic Ocean, which extends through Iceland and across the North Pole. This crack emerged 180 to 200 million years ago, and as it did, North and South America started to rotate away from Africa. That crack continues on the other side of the world as the East Pacific rise, which cuts through the Gulf of California and then heads due south to Easter Island. These cracks, which are the places where the lithosphere is under extension, control the fate of Earth.

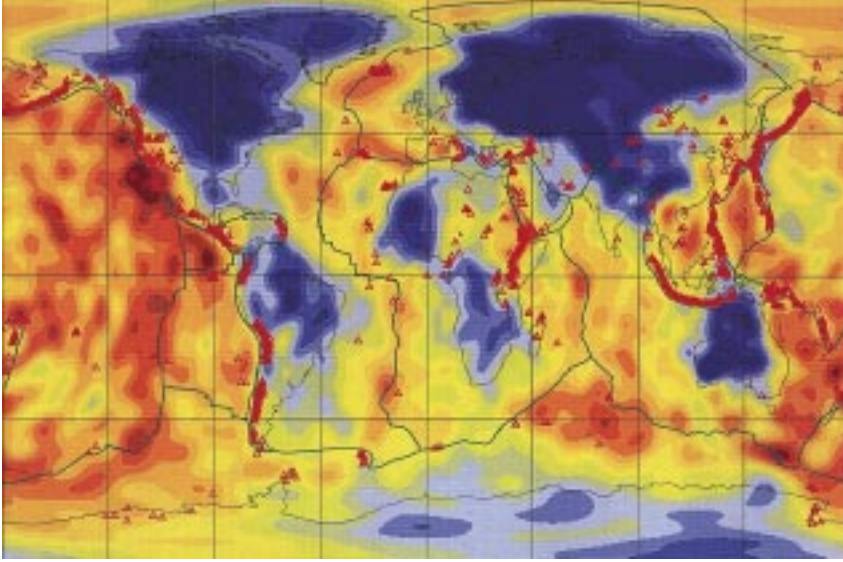
Midoceanic ridges are created by plates being pulled apart. The plate breaks in the middle. It's thin and hot, and new magma comes up through the crack. Then, as the plates continue to be pulled away, the magma freezes and makes new oceanic lithosphere. So the oceanic lithosphere is hot along the ridge in the middle of the ocean, and then cools and gets thicker and thicker, and older and older, as it moves away from the ridge. There's no doubt that the volcanoes along the mid-Atlantic ridge are due to plate-tectonic forces causing tension cracks that then allow the magma underneath to come up through them. When we compared our early tomographic cross sections with geological maps, we found that a seismically slow, very hot region extending down to about 200 kilometers occurred at every crossing of a midoceanic ridge. These hot regions are usually represented by red in our images.

At the other end of the cycle, the lithosphere that has formed at a ridge dives underneath a



These maps of part of the northern hemisphere (left) and southern hemisphere (right) show the ages (colors) of various parts of the seafloor; the youngest seafloor is red, moving to orange, yellow, green, and finally blue in the oldest parts. Earthquakes (black and white circles) and volcanoes (yellow triangles) occur mainly at plate boundaries.

(Prepared with David Sandwell.)



The tomographic map at left of the seismic velocities at a depth of 150 kilometers shows fast, blue regions (cold) and slow, red ones (hot or containing melt). Most of the blue regions are roots of old continents. The most ancient slabs appear as blue in the map below at a depth of 400 kilometers. The red triangles indicate volcanoes. Plate boundaries are shown as black lines. (Courtesy of Hendrik van Heijst.)

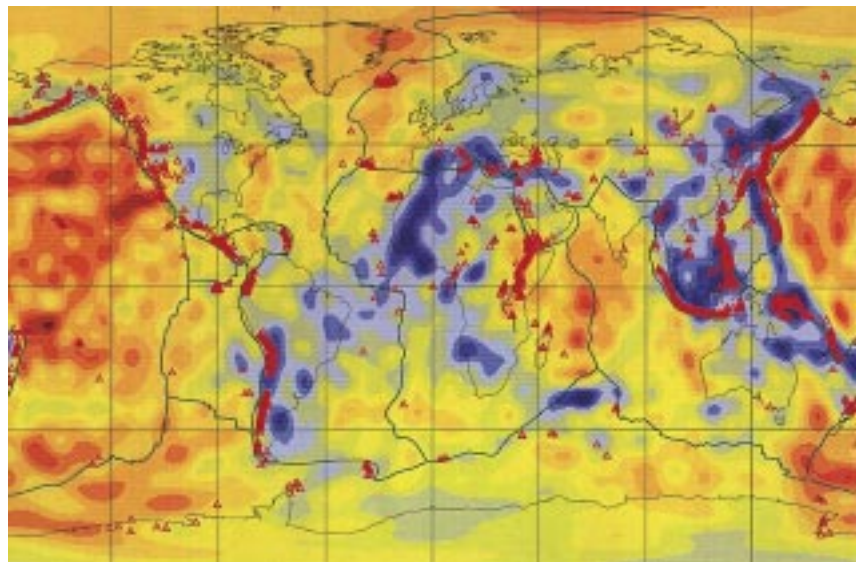
continent in a trench and disappears into the mantle again. These deep-sea trenches, also called subduction zones, encircle the Pacific Ocean. The nearest ones to us are in Central America and off the coast of Washington, Oregon, and British Columbia. The Alaskan coast and the Aleutians are also shaped by trenches, where the plate slides down into the mantle. Because the plate was at Earth's surface, it should be cold when it sinks, and seismic tomography can detect these cold regions (which we usually indicate as blue) going down to 600 kilometers. Numerical correlations show that these slabs may end up in the middle mantle, the mesosphere, between about 600 and 1,000 kilometers depth.

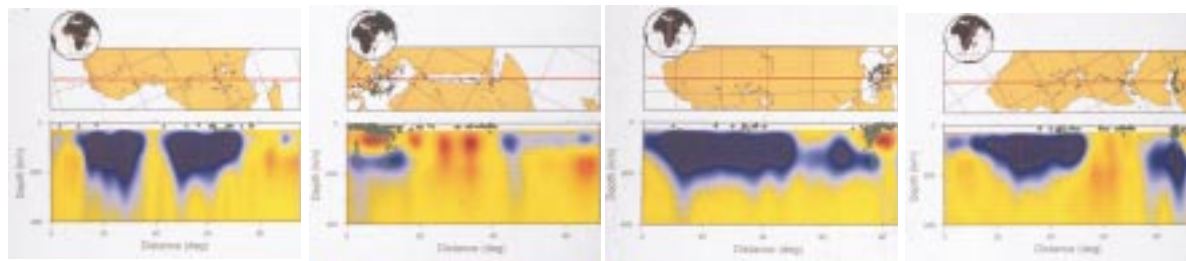
Tomographic images also show that the East Pacific rise extends right under western North America. The mantle under California is just as hot as it is under the spreading ridge to the south, where molten rock is spilling out on the seafloor. In fact, the San Andreas fault is part of the

Pacific–North American plate boundary. A rise and trench system once existed off the California coast, but the ridge was overridden by North America. The ridge and trench collided and annihilated each other, and now western North America sits on top of what used to be the East Pacific rise. The tomographic images show reddish regions underneath, which imply temperatures that are very close to or above the melting point. It is only the cold, strong plate under California that is keeping the magma down.

We have also discovered that continents have deep roots extending down to 200 kilometers or so. Every time a seismic wave crosses an ancient part of a continent, we see big blue roots. These deep roots are, in fact, centered on the oldest part of the continents, under Canada, Brazil, Siberia, India, the Baltic states, and parts of Africa. These ancient cores of continents are called cratons, and form the thickest parts of Earth's outer shell. These parts have had longer to grow and longer

Do plumes cause the cracks and volcanoes to form?
Or do plate tectonics and lithospheric architecture
control the locations of cracks and volcanoes?





These four tomographic cross-sections across Africa show the cold roots of ancient parts of the continent (cratons) in blue. The hot (red) upwelling areas are feeding the volcanoes in Ethiopia. (Courtesy of Hendrik van Heijst.)

The globe at right indicates where cold slabs have disappeared into the mantle during the last two supercontinent cycles. These regions should still be cold and show up as blue in tomographic images. The locations of oceanic ridges for the past 100 million years are cross-hatched.

to cool. Seismologists can now find these ancient cores of continents just by looking at their seismometers, without ever looking at a rock or analyzing it in a geochronological laboratory.

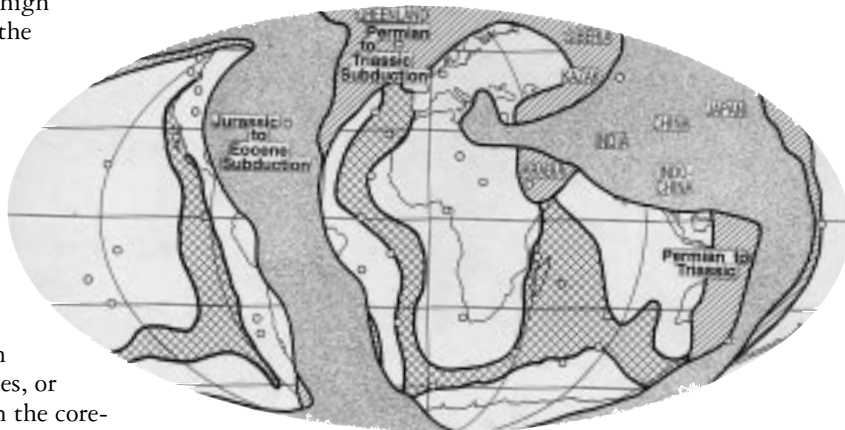
The features that we see at the surface of Earth—ridges, plates, continents, and trenches—also show up deep below. Our tomographic maps show us the ancient cores of continents, the thickening of the plate as it moves away from a ridge, and evidence of subduction zones. We also see plate tectonics impressing itself on the fabric of the underlying mantle. We see hot, upwelling mantle under thin lithosphere and cold, downwelling mantle under thick or old lithosphere. We can see mantle being sucked up at spreading ridges.

At depth the whole Pacific mantle has very low seismic velocities and very high temperatures compared to the continents. But volcanic chains occur in only a few places in the middle of the Pacific plate. The question is: is that molten rock associated with what's happening in the middle of the plate or underneath it? Is the Pacific plate under extension there, allowing molten rock to come up in volcanoes, or does a plume come up from the core-mantle boundary? There are few active volcanoes in the middle of the north Pacific. Is there one plume or just one place where stresses in the Pacific plate allow magma to come through?

Where do volcanoes occur in the plate-tectonics scenario? There are very few volcanoes under thick, cold lithosphere. The ancient lithosphere with continental crust on top has two roles. First, it affects the flow in the mantle by causing cold downwellings. But in the case of a superconti-

nent, the heat can't get out; so it also acts as an insulating blanket, allowing temperatures to build up underneath. The lithosphere underneath old continents is quite strong and able to support itself and is not likely to crack, except along the edges of cratons.

At a depth of 50 kilometers, which is just below the continental crust, cratons show up as high-velocity, or cold, regions. Continental flood basalts were created at various times by the eruption of large amounts of magma, and one such basalt, the Deccan Traps in India, formed 65 million years ago just when the dinosaurs went extinct. Indeed, many of these continental flood basalts happen to correspond to extinctions in the geological record, but what's interesting for tectonics is that they all occur right on the edges of



the cratons, the thickest, coldest, and strongest parts of the plates. Somehow, cratons affect the flow of the hot mantle underneath.

At the beginning of this article I mentioned the opposite-hemisphere dichotomy, which I'd now like to pursue a bit further. About 120 million years ago all the continents were joined together in one supercontinent. For some reason it broke



One hundred and twenty million years ago the Pacific plate was new and only a small fraction of its present size. As the surrounding plates were pulled away by sinking slabs around their edges, the Pacific plate grew. Triple junctions occur where three plates join; this is where large oceanic plateaus are constructed. (Courtesy of Paul Heller, University of Wyoming.)



up along weak zones that eventually became the midocean ridges. South America moved away from Africa; North America moved away from Eurasia and Africa. At the same time, on the other side of the world, a series of plates was reorganizing. There were a bunch of plates on the floor of the Pacific Ocean at that point, but one of them, now called the Pacific plate, grew until it eventually filled up almost the entire Pacific basin, and the other plates disappeared underneath the continents that had moved over into the Pacific hemisphere. So the breakaway of North America and the breakup of plates on the other side of the planet are likely related. What probably happened is that the Pacific ridges and trenches, as they collided along the coast of the supercontinent, allowed it to go into extension and break up.

Both the breakup of the supercontinent, which is called Pangaea, and the reorganization of the antipodal ocean plates resulted in vast outpourings of magma. Those in the Pacific hemisphere resulted in what are called oceanic plateaus, California-sized edifices of shallow seafloor underlain by about 20 kilometers of basalt. These plateaus all formed at the boundaries where three plates came together, the so-called triple junctions. As the other continents drifted away from Africa, opening up the Atlantic and Indian oceans, the plates in the Pacific hemisphere kept reorganizing, and the triple junctions jumped around, triggering a new burst of igneous activity each time. In the plume hypothesis, each burst of magma was caused by a plume entering the shallow mantle from below. In the plate hypothesis, it is the new ridges and triple junctions that stimulate a transient burst of magmatic activity.

The supercontinent stays together as long as it's under compression, or as long as subduction is holding it together. Subduction zones and deep-sea trenches are also called collision or convergent zones—they compress the continent. But if for some reason we remove that compression, the

continent can fly apart. Western North America exhibits a good example of this. When the ridge and trench collided, annihilating each other and forming the San Andreas fault, they removed the force that was holding North America together, resulting in extension. Tension is as important to tectonics as it is to architecture (think of domes, arches, and flying buttresses); tectonics is, in a way, a kind of architecture.

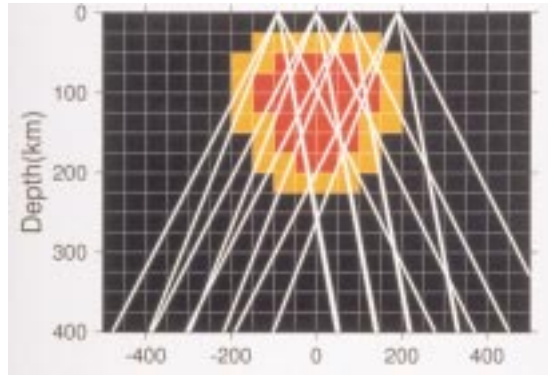
Architecture may be one metaphor for plate tectonics, but I like to use beverages to illustrate the various ideas of what causes the convection currents in the mantle. The theory of the mantle as a pot on a stove, being heated from below by the core (in some experiments, hot fluid is actually poured as from a teapot into the bottom of a tank to simulate mantle convection) was by and large invented in England, where pots on stoves and hot tea are part of the culture. Later, the Australians, who drink a lot of beer, also got interested in mantle convection. Beer has bubbles coming up from the bottom, so the Aussies, too, were sympathetic to this kind of bottoms-up view of Earth.

In this country, however, we like to put ice cubes in our drinks. We also invented the microwave oven, which allows us to heat our American fast food from within; you don't have to wait for it to heat from below like a pot on a stove. Perhaps that is why some of us believe that the mantle is heated from within by the decay of radioactive elements and is cooled from above by ancient continents and subducting slabs poking down into the mantle like ice cubes. Continents themselves can also act as ice cubes to some extent and can cause material in contact with their undersides to cool and slide down.

Heating a glass of tea in a microwave will make it convect by heating it from within; ice cubes in a glass of tea will also cause convection by cooling from above. So we can cool off the mantle from above while heating it from within. This is the top-down hypothesis—the idea that plate tecton-



Seismic CAT scans of Earth's interior can be misleading. The image at the immediate right is a model of a large magma chamber under Iceland; the white lines are rays from distant earthquakes. In optical terms, there is not much parallax with this data—there is no depth perception. When the data from these rays are analyzed (inverted), we get the view at far right, suggesting a deep conical or cylindrical structure extending to 400 kilometers in depth. The “real” structure was all above 200 kilometers. (Courtesy of William Keller.)

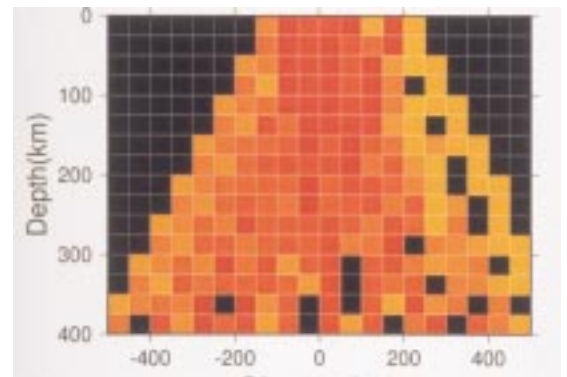


ics might be driven, or modulated, from the top rather than the bottom.

We have to decide which one of these metaphors is most accurate and consider other things that are happening. Now we come back to the volcanoes and the question of whether they come from deep plumes or from a shallow part of the mantle. A midocean ridge forms as a crack and then it spreads apart, allowing hot magma to well up and melt. Enormous amounts of magma from large sections of the mantle are involved in this process. Magma can also be found in the ocean islands; they're called ocean-island basalts, which means they're of volcanic origin. Ocean islands represent a trivial amount of basalt compared to the midocean ridge system; they also generally form on older lithosphere. The magmas that rise to become ocean islands have some preexisting crust, some sediments, and various kinds of mantle to go through before they erupt, so chemically they look different from the midocean ridges.

While basalts along midocean ridges are relatively uniform in composition and appear to be little contaminated by sediments, crust, or older mantle, ocean-island basalts are not all the same and appear to be variably contaminated by materials that originated at Earth's surface. Do these various kinds of magmas come from different depths in the mantle? Do we have to go all the way down to the bottom of the mantle in order to get ocean-island basalts?

The contaminants in ocean-island basalts may have been acquired from Earth's shallow layers, but here it gets complicated. A midocean ridge samples the mantle as a steam shovel does: it takes huge gobs all at once and mixes everything that's down there. Since ocean islands and continental volcanoes are much smaller in volume, they sample the mantle more like tweezers. It's something like eating a fruitcake: if you take a big bite of the fruitcake, it tastes like a mixture of all kinds of things, but if you take a pair of tweezers and pick



out a tiny piece at a time, sometimes you'll taste a candied pear, sometimes an apple or a raisin or some dough. Each of these would taste quite different from the whole fruitcake. Can this difference in sampling account for the difference in chemistry of ocean islands? Since midocean ridges must process 10 times as much mantle each year as ocean-island volcanoes do, they can't afford to be too choosy. Island volcanoes, on the other hand, take small, dainty bites out of the mantle.

Most volcanic islands are far from land, and, since most seismometers are on land, it's difficult to obtain detailed seismic images of them. We can, however, obtain clues from studies of other volcanic regions. For example, a study of Yellowstone by Gene Humphreys (PhD '85; now on the faculty of the University of Oregon) discovered very low seismic velocities indicating hot mantle extending down to about 200 kilometers underneath Yellowstone and its vicinity. But it doesn't go any deeper than 200 kilometers. The Wyoming craton (the equivalent of an ice cube or two) also extends down to 200 kilometers. If Yellowstone were a glass of iced tea, we'd have cold downwellings under the ice, and then the warmer part would come up between the ice cubes. This experiment seems to indicate that at least some volcanic regions have fairly shallow roots.

Another experiment, in Iceland, where seismometers received signals from the other side of the world, revealed what looked like a plume going down to 400 kilometers. This seemed to confirm the deep, narrow-plume hypothesis, but one of my students, Bill Keller, has shown that a very shallow source, less than 200 kilometers in depth, could satisfy the same data. Seen this way, the Iceland image looks very much like the Yellowstone image, and we might have the ice-cube, crack, shallow-mantle explanation again. There are large regions of hot mantle under Iceland, Yellowstone, Hawaii, and most hot-spots, but the issue is whether the magma is

When you follow this scenario through, from impact and melting to freezing and recrystallization, you end up with a laminated or layered model much like Dante's.

focused to the volcano by a crack or a plume.

The mantle below 1,000 kilometers looks very different from the mantle at shallow depths and bears little resemblance to shallow lithospheric architecture or geology. It may be doing its own thing, isolated from the yet deeper mantle. The mantle below 2,000 kilometers is apparently a still different world, where violent convection seems to be taking place. Perhaps here the iron core really is acting like a hot stove.

I speculate that the mantle may be divided into three chemically distinct regions—a tripartite mantle, to go along with the tripartite Earth (crust, mantle, core). This is much more complicated than current Earth models, but it doesn't yet approach the complexity of Dante's *Inferno*.

In my conception, Earth started out with a primordial mantle (remember Descartes) that was basically made up of meteorites. But during accretion the mantle melted, and the light stuff ended up on top and the dense stuff ended up down below. Because of very large early impacts, the whole mantle most likely was melted as it was being formed, and the light stuff came to the top along with the elements that preferred to migrate with the melted material, leaving behind a dense lower mantle depleted of its basalt-forming and heat-producing elements. When you follow this scenario through, from impact and melting to freezing and recrystallization, you end up with a laminated or layered model much like Dante's, with the lightweight sinners up on top and the heavyweight sinners down below. With this scenario we can explain the dynamics and chemistry involved in plate tectonics and volcanoes by recycling just the outer part of the planet. Although many Earth scientists think that they are routinely sampling material from just above the core, or even pieces of the core, a consistent picture can be formed by recycling surface materials down to 800 or 1,000 kilometers and then back again. Much of the "contamination" that makes basalts

from ocean islands so distinctive in their chemistry—and different from midocean ridge volcanoes—actually leaves the downgoing slab before it penetrates deeper than 200 kilometers.

We are far from converging on a commonly accepted view of the evolution of our planet. Unlike in physics, the end—the final solution, the Grand Unifying Theory—is not in sight. A cold, refractory planet, composed in part of original primordial matter, is one reigning view. Another is that the mantle is homogeneous and material cycles from top to bottom and back. Yet another view holds that volcanic regions such as in Hawaii, Iceland, Yellowstone, and the Galapagos are fueled by hot plumes from the bottom of the mantle.

My view is that Earth's accretion destroyed the original material, which then segregated itself into the various layers, sorted by density. The mantle is chemically stratified. The magmasphere produces volcanoes only where the outer shell allows it. Lithospheric architecture and stress in the shell controls volcanism. This is a minority view, but it does at least provide a Grand Unifying Hypothesis. □

Don Anderson presented his iced-tea view of Earth in a February Watson lecture, from which this article is adapted. Shortly before, in December, he was one of nine Americans awarded the 1998 National Medal of Science for his decades-long work on the dynamics of the deep parts of the planet. Anderson first came to Caltech as a graduate student, earning his MS in 1958 and his PhD in geophysics and mathematics in 1962. He joined the Caltech faculty in 1963, becoming full professor in 1968, and since 1989 has held the Eleanor and John R. McMillan Professorship in geophysics. He was director of the Seismological Laboratory from 1967 to 1989. In 1998 Anderson received the Crafoord Prize—the Nobel of geophysics.



PICTURE CREDITS:
10, 17 – Charlie White

The continents and plates visible on the surface of Earth (if it could be seen, as at right, stripped of oceans and clouds) are formed by processes in Earth's interior.